INTERNATIONAL JOURNAL FOR NUMERICAL AND ANALYTICAL METHODS IN GEOMECHANICS
Int. J. Numer. Anal. Meth. Geomech., **23**, 1337–1348 (1999)

PULLOUT TEST MODEL FOR EXTENSIBLE REINFORCEMENT

N. GURUNG[1,*,†], Y. IWAO[1,‡] AND M. R. MADHAV[2,‡]

[1] *Department of Civil Engineering, Saga University, Saga 840-8502, Japan*
[2] *Department of Civil Engineering, Indian Institute of Technology, Kanpur, India*

SUMMARY

A formulation for the analysis of pullout test on highly extensible planar reinforcement is presented. The non-linear differential equation for pullout mechanism was expressed in non-dimensional form and solved numerically using the Gauss–Siedel technique. Parametric study was carried out for various ranges of relative stiffnesses, and relative bond resistances. Normalized load–displacement relations and the variations of pullout force and reinforcement displacements along the length of reinforcement are presented graphically. A method for the estimation of the interface interaction parameters from a pre-failure test is also given. The numerical predictions compare well with the available experimental pullout test results for various geotextiles, polymers and nylon geosynthetics. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: extensible reinforcement; geosynthetic; hyperbolic model; interaction mechanism; pullout test

1. INTRODUCTION

Field and laboratory pullout tests are widely used to interpret the interaction mechanisms and to evaluate the interface interaction parameters between reinforcement and soil. Pullout test for soil inclusions is used for checking the strength, integrity and effectiveness of the soil-reinforcement. McGown *et al.*[1] distinguish between the extensible and inextensible reinforcements in terms of different load–deformation responses (Figure 1). Basic design criteria for reinforced earth structures demands checking for external and internal stability.[2,3] The pullout failure and shear failure between soil and inclusions are internal stability problems. The reinforcement in the direction of tensile strain strengthens the soil.[4] The soil–reinforcement interaction mechanisms can be simplified to either direct shear or pullout by neglecting bending resistance of reinforcement.[5] The use of the critical state angle of friction of soil instead of the peak angle is empirically suggested[6] to estimate the bearing resistance in the case of extensible reinforcements due to different degrees of mobilization of bearing resistance along the length of the reinforcement. Many interface formulae are evolving based on the various interface bond resistance models. Based on the field pullout tests on polymer geosynthetics, Konami *et al.*[7] proposed a simple elastic model for

*Correspondence to: N. Gurung, Department of Civil Engineering, Saga University, Saga 840-8502, Japan
† Doctoral student
‡ Professor

CCC 0363–9061/99/121337–12$17.50

Received 29 January 1998
Revised 29 January 1999

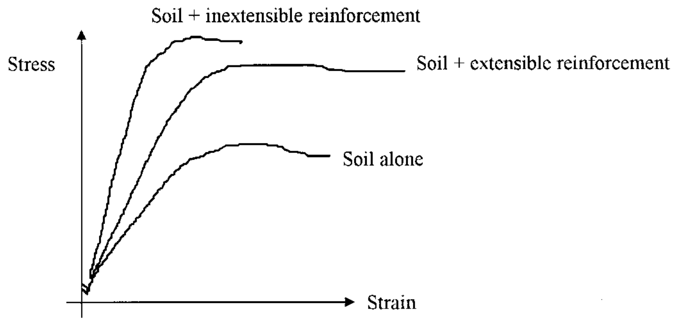

Figure 1. Load–strain relationship for soil, soil reinforced with extensible and inextensible reinforcements (McGown *et al*.[1])

polymer strips. The pullout test results in terms of variation of mobilized tension, pre-yield and post-yield behaviour, effective and extended lengths of the reinforcement, etc., are fairly well predicted. For the analysis of planar reinforcement in pullout, Abramento and Whittle[8] purpose a theory based on shear-lag. Segrestin and Bastick[9] compare pullout capacity of extensible and inextensible reinforcements. Sobhi and Wu[10] have contributed an interface model for extensible reinforcement based on rigid–plastic shear stress mobilization while Long *et al.*[11] use curve fitting by parabolas to describe non-uniform shear distribution at the reinforcement–soil interface.

Numerical modelling by using finite element analysis can also be used to simulate the pullout operation. To simulate the non-linear pullout load and strain distribution along the reinforcement, Yogarajah and Yeo[12] used the CRISP finite element program.[13] The values of the interface shear modulus were calibrated from the evaluated elastic modulus that was obtained from measurements. Joint elements of Goodman *et al.*[14] were used to simulate the slip plane interface. Kalikan and Li[15] report some fundamental deficiencies of such commonly used zero thickness interface elements. This layer elements of Desai *et al.*[16] may reduce some of the numerical errors. Bergado *et al.*[17] evaluated the reinforced embankment system by using finite element analysis, where updating the nodal co-ordinates simulated large deformation phenomenon. The constitutive law of interface shear stress–displacement was based on hyperbolic relation. The accuracy of such numerical simulation depends on the accuracy of detailed parameters of soil, reinforcement and joint interface.

Finite Difference Method (FDM) may be considered as a particular case of Finite Element Method (FEM) with particular choice of shape functions. The simplicity of the FDM regarding the preparation, programming, input, output, interpretation and understanding as compared with the more general but complex case of FEM, is another advantage that has been appreciated by practising engineers. To avoid computational efforts, detailed parameters and memory size, a simple numerical analysis by FDM that is also capable of simulating small to large strain responses of planar reinforcements in field and laboratory pullout test is presented in this paper.

In confined pullout failure, high non-linear extension of only a part of the length may be attributed to the variation in mobilization of interface shear resistance along the reinforcement. Madhav *et al.*[18] proposes a bilinear model to predict the pullout response of highly extensible planar reinforcements. The model is extended for the prediction of non-linear responses during pullout test for highly extensible geosynthetic by incorporating a hyperbolic shear stress–displacement relation along the interface. This paper describes the numerical (FDM) solution for

non-linear displacement, strain, tension and shear stress variations during the pullout test. The predictions are compared with the results of laboratory and field pullout tests on geotextiles and nylon as well as on polymer strip geosynthetics.

2. PROBLEM FORMULATION

2.1. Theoretical formulation

Consider a pullout test on a geosynthetic planar reinforcement (Figure 2). The applied pullout force, T_0, mobilizes interface bond stresses, τ, along the length of reinforcement. It is assumed that the tensile strength, T_y of the reinforcement is significantly high, compared to the pullout force so that reinforcement breakage is not possible. A pullout test integrates the variation in the tensile shear stress and displacement along the reinforcement, whereas direct shear test provides a local shear stress–displacement relationship. The interface bond stresses, τ, are governed by the interface response (Figure 2 (c)) and may be obtained from a typical direct shear test. The strain softening as observed in some cases will not be dealt with here. Theoretical modification may be extended to account the cyclic shear behaviour with massing hysteretic unload–reload behaviour. Cai and Bathurst[19] illustrate cyclic unload–reload interface model for polymeric reinforcement that accounts slips.

The total resistance in pullout is expressed as the sum of the interface shear resistances along the length of the reinforcement. It can be observed that the interface bond resistance increases

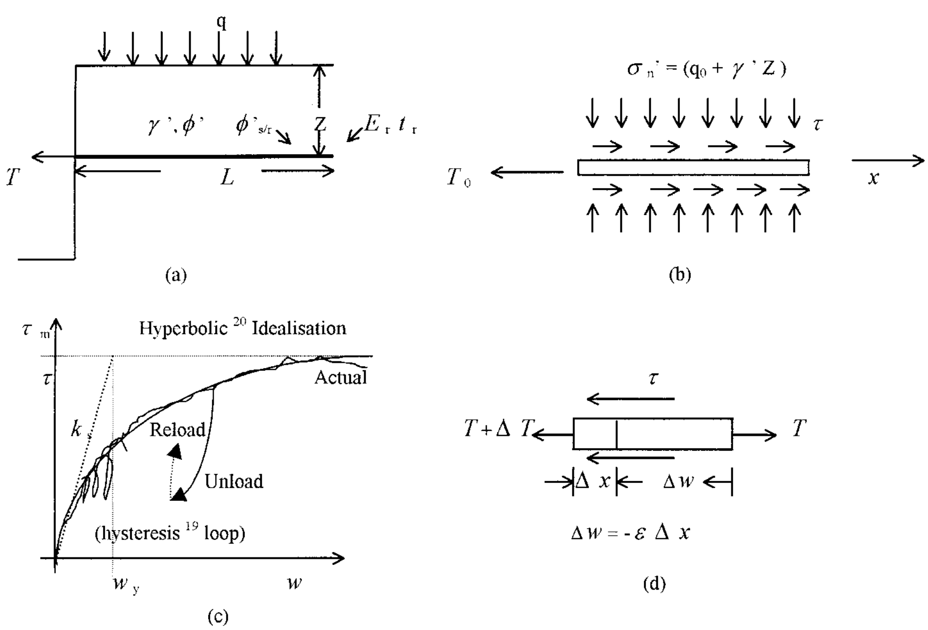

Figure 2. (a) soil-reinforcement system; (b) forces on reinforcement; (c) stress–displacement curve; (d) free body of reinforcement

with relative displacement, w, and reaches asymptotically the maximum bond resistance, τ_m, at failure by slip. The actual τ vs. w curve may be simplified by a hyperbolic response[20] curve, as

$$\tau = \frac{w}{a + bw} \tag{1}$$

where $a = 1/k_s$ and $b = 1/\tau_m$, k_s is the initial slope of τ vs w curve and τ_m the maximum unit bond resistance of the reinforcement. The maximum value τ_m of the inclusion in granular fill is limited to

$$\tau_m = \sigma'_n \tan \phi'_{s/r} = (q_0 + \gamma' Z) \tan \phi'_{s/r} \tag{2}$$

where $\sigma'_n = (q_0 + \gamma' Z)$ is the normal stress on the interfaces, q_0 the surcharge stress, γ' the effective unit weight of the fill, Z the depth of the reinforcement and $\phi'_{s/r}$ the effective interface friction angle.

In this study, the reinforcement is considered to be highly extensible as is likely in the case of some geosynthetics and geomembranes. Therefore, considering (Figure 2(d)) the extended length of a small differential element of length, Δx, and of unit width of the reinforcement and neglecting boundary effects, the equilibrium of horizontal forces is satisfied by

$$(T + \Delta T) - T + 2\tau(\Delta x + \Delta w) = 0 \tag{3}$$

where T and $(T + \Delta T)$ are the pullout forces per unit width in the reinforcement on the left and right ends, τ the mobilized bond resistance and Δw the elongation of the element of length, Δx, The elongation, Δw, is related to the strain, ε, as

$$\Delta w = -\varepsilon \Delta x \tag{4}$$

while the strain, ε, is related to the tensile force per unit width, T, as

$$\varepsilon = T/E_r t_r \tag{5}$$

Equation (1) can be simplified as

$$\frac{dT}{dx} + 2\tau(1 + \varepsilon) = 0 \tag{6}$$

Noting that for the x-axis positive to the right, i.e. $\varepsilon = -\,dw/dx$, equations (5) and (6) are combined to give

$$E_r t_r \frac{d^2 w}{dx^2} + 2\tau\left(\frac{dw}{dx} - 1\right) = 0 \tag{7}$$

The above equation governs the response of the interface during pullout. Substituting equation (1) in equation (7) and expressing it in non-dimensional form with the normalized yield displacement, $w_y = \tau_m/k_s$ and the length, L, as $W = w/w_y$. and $X = x/L$, one gets on simplification

$$\frac{d^2 W}{dX^2} + \frac{\alpha W}{(1 + W)}\left\{\beta \frac{dW}{dX} - 1\right\} = 0 \tag{8}$$

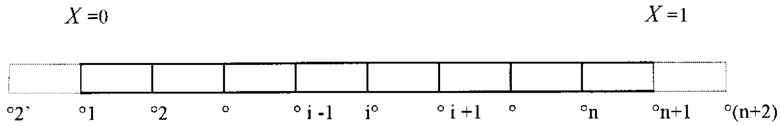

Figure 3. Discretisation elements for reinforcement

where $\alpha = 2k_s L^2/E_r t_r$ is the relative stiffness and $\beta = w_y/L$ are the relative displacement parameters. Equation (8) is a non-linear differential equation. The close form solution of Sobhi and Wu[10] could be theoretically derived from the above formulation with a finite value of $\alpha\beta$ but with either $\alpha \to \infty$ or $\beta \to 0$. Discretizing (Figure 3) the reinforcement into 'n' elements each of length $\Delta L = L/n$ or $\Delta X = 1/n$ and expressing the derivatives equation (8) in finite difference form, the displacement, W_i, at node ith, is

$$W_i = \frac{W_{i-1} + W_{i+1}}{\{2 - \alpha\,[\beta n((W_{i+1} - W_{i-1})/2) - 1]/\{n^2(1 + W_i)\}\}} \tag{9}$$

The boundary conditions at $X = 0$, $\varepsilon = T_0/E_r t_r$ or $\mathrm{d}W/\mathrm{d}X = -\alpha T^*$ and $X = 1$, $\varepsilon = 0$ are utilized to solve for displacements at nodes 1 and $n + 1$, by assuming two fictitious nodes, $2'$ to the left of node '1' and $(n + 2)$ to the right of node $(n + 1)$, where the normalized displacements become

$$W'_2 = W_2 + 2\alpha T^*/n \tag{10}$$

and

$$W_n = W_{n+2} \tag{11}$$

with $T^* = T_0/T_m$ and $T_m = 2\tau_m L$ is the maximum pullout force per unit width.

2.2. Estimation of interface interaction parameters

The various interface interaction parameters for the field and laboratory pullout experiments may be estimated from the pre-failure pullout test. For any given overburden pressure, σ'_n, the interface shear stress $\tau_m = \sigma'_n \mu$ and the total pullout resistance can be evaluated as $T_{max} = 2\tau_m L$ per unit width. The product of interaction parameters is $\alpha\beta = T_{max}/E_r t_r$. For a trial value of α, the corresponding β value can be obtained. Analytical solution of equation (7) at small pullout force range will result in

$$\frac{w}{T} = \frac{L}{\sqrt{\alpha} E_r t_r \tanh(\sqrt{\alpha})} \tag{12}$$

Equation (12) expresses the initial slope of the displacement vs. pullout force in terms of the reinforcement characteristics, E_r, t_r and L, and the interface shear stiffness, k_s Equation (12) may be used to estimate the value of α from the initial slope of the force–displacement curve of the pullout test. For known values of E_r, t_r and L, the value of k_s may thus be estimated from the initial slope of displacement–pullout force curve.

3. RESULTS AND DISCUSSION

The solution for the variations of normalized displacements, strains and normalized pullout forces along the reinforcement length are obtained numerically. Parametric studies have been carried out for wide ranges of interaction parameters: $T^* = 0$–$1{\cdot}0$, $\alpha = 2$–200 and $\beta = 0{\cdot}0001$–$0{\cdot}2$; where $\alpha(= 2k_s L^2/E_r t_r)$ is a relative stiffness parameter and $\beta\ (= w_y/L)$ is a relative displacement parameter. The product $\alpha\beta\ (= T_{max}/E_r t_r = 2\sigma'_n \mu L/E_r t_r)$ is a function of the maximum pullout force (a function of the normal stress, the coefficient of interface bond resistance and the length) and the reinforcement stiffness and is independent of the unit shear stiffness, k_s.

The displacement, W_0, response with pullout force, T^*, is presented in Figure 4, for $\beta = 0{\cdot}01$ and for various values of the relative stiffness parameter, α. The displacements increase non-linearly with the pullout force T^*. The rate of increase in W_0 is more at higher pullout forces, as a consequence of the elements near the pullout force end attaining their maximum bond resistance values and slipping without mobilizing any additional bond resistance. Theoretically, as the pullout force approaches the limit $T \rightarrow T_m\ (= 2\tau_m L)$ or the normalized pullout force T^* tends to 1·0, slip failure occurs and the displacement, W_0, tends to infinity. The displacements at any given pullout force, T^*, increase with an increasing value of α. For a given soil–reinforcement interface, the values of α increase, either if the length, L of the reinforcement, is larger or if the stiffness, E_r, of the reinforcement is smaller. In either case, it is justifiable that displacements for all pullout force levels increase with α (because of longer or highly extensible reinforcement).

The influence of the relative displacement parameter, β, on the displacement–pullout response is depicted in Figure 5 for $\alpha = 2$. For a constant value of interface bond stiffness, k_s, i.e. keeping a constant value of $\alpha = 2k_s L^2/(E_r t_r)$ and varying value of $\beta = \tau_m/(k_s L)$ implies that the maximum bond resistance, τ_m, is varying. Higher the value of β, higher will be the maximum pullout force, τ_m and larger will be the displacement, w_y, for attaining the yield or the maximum bond resistance. Consequently, the curves for higher values of β have an extended linear portion and exhibit relatively smaller pullout end displacements at any pullout force level. For example at $T^* = 0{\cdot}4$ ($\alpha = 2$), the displacements are 0·88, 0·901, 0·923 and 0·9238 for β values of 0·001, 0·05, 0·1 and 0·2, respectively.

The product $\alpha\beta = 0{\cdot}1$ (keeping constant, the displacement responses at various pullout forces for different combinations of ($\alpha_1 = 10$, $\beta_1 = 0{\cdot}01$), ($\alpha_2 = 5$, $\beta_2 = 0{\cdot}02$), ($\alpha_3 = 2$, $\beta_3 = 0{\cdot}05$) are

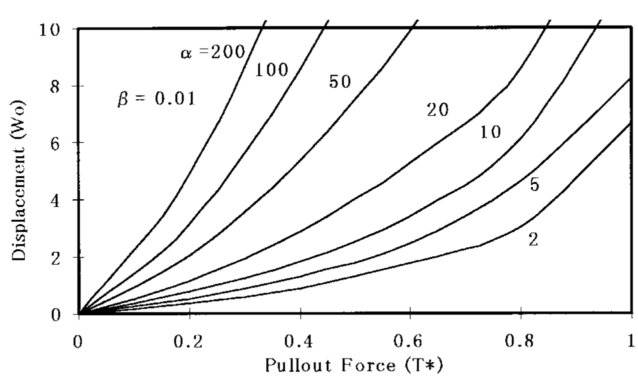

Figure 4. Displacement vs. pullout force response ($\beta = 0{\cdot}01$)

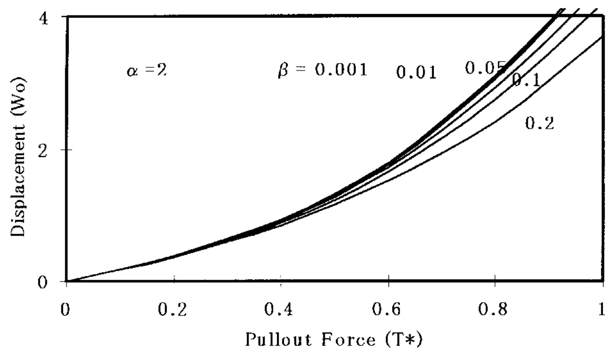

Figure 5. Displacement vs. pullout force response ($\alpha = 2$)

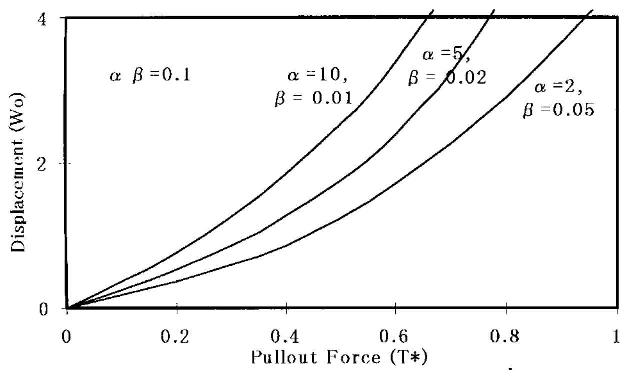

Figure 6. Pullout force vs. displacement response ($\alpha\beta = 0{\cdot}1$)

shown in Figure 6. A remarkable decrease of displacements at any given level of pullout force can be noted with decreasing α values. The displacements are very sensitive to the input values of β. Low values of β ($= w_y/L = \tau_m/k_s L$) imply small unit bond resistance, very long reinforcement or very stiff interface response (high k_s). Thus the response curves are highly non-linear for low values of β (low bond strength, long reinforcement or very high interface stiffness). Thus Figure 6 brings out the importance of considering both the stiffness and the maximum bond resistance of the interface. The displacement dampening kind of mechanism may be imagined for reduced values of α. Also, higher value of β indicates reduced stiffness of the interactive media.

The variations of the pullout forces along the length of the reinforcement at various pullout force levels ($T^* = 0{\cdot}95$, 0·8, 0·6, 0·4 and 0·2) are shown in Figure 7. Consideration of the pullout force curves for different combinations of α and β brings out the effect of the interface stiffness. Curves given for the two pairs of α and β ($\alpha = 5$, $\beta = 0{\cdot}1$ and $\alpha = 50$, $\beta = 0{\cdot}01$) but with the same product value of 0·5, demonstrate the effect of k_s or α on the pullout interactions. Stiffer the reinforcement, longer would be the length of bond resistance mobilised at all stress levels. For any given interface bond strength (τ_m) and reinforcement characteristics (E_r, t_r and L), the product $\alpha\beta$ is unique but the interface bond stiffness, k_s, has significant influence on the pullout response for extensible reinforcement.

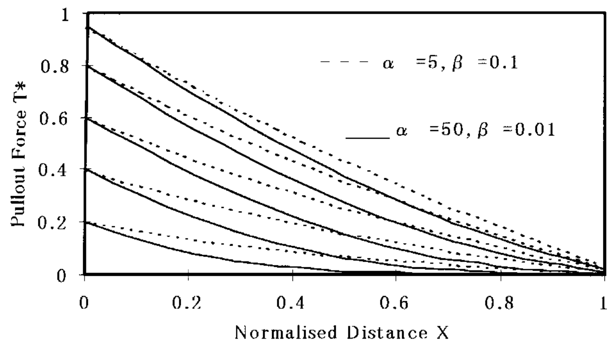

Figure 7. Pullout force variation along distance ($\alpha\beta = 0{\cdot}5$)

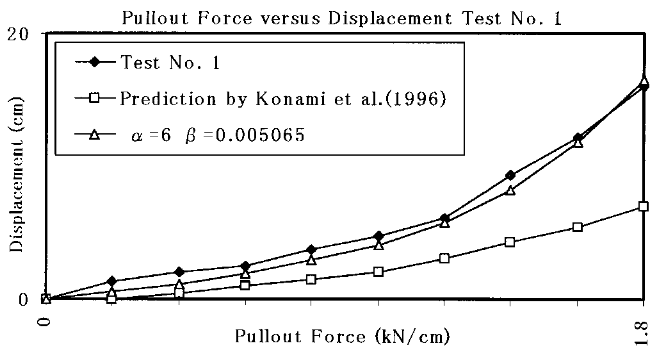

Figure 8. Pullout force vs. displacement response for Test No. 1[7]

4. VERIFICATION OF THE PROPOSED MODEL

Field pullout tests on polymer strip geosynthetic reinforcements as reported by Konami *et al.*[7] with a fill of unit weight 18·6 kN/m^3 and reinforcements of length 3·5 m, are analysed. The friction angle, $\phi'_{s/r}$ was 38·2° from direct shear tests. From the test data, the normal stress σ'_n, shear stress $\tau_m = \sigma'_n \tan \phi'_{s/r}$ and the maximum pullout force $T_{max} = 2\tau_m L$ for various depths of reinforcement are estimated. Knowing the effective values of $E_r t_r$, the products $\alpha\beta = T_{max}/E_r t_r$ are estimated as 0·03015, 0·03015, 0·0232, and 0·03608 for tests 1, 2, 3, and 4, respectively. The pullout responses for the trial values of α and β, the predictions from Konami *et al.*[7] based on their approach (based on full mobilisation of full bond resistance over an effective length) and the experimental test results are compared in Figures 8–11. The predictions are close to the measured values.

The pullout test responses on 300 mm long geotextile reported by Sobhi and Wu,[10] are compared in Figure 12. Sobhi and Wu,[10] obtained a closed-form solution for pullout force assuming full shear resistance mobilization and rigid plastic type of response. For normal stress of 40 kPa, the maximum pullout force was 6·96 kN/m. Assuming μ equal to 0·29 and with geotextile stiffness $E_r t_r = 31{\cdot}8$ kN/m, the product $\alpha\beta$ was estimated to be 0·212. The predictions of the proposed model with $\alpha = 9$, $\beta = 0{\cdot}0243$ compare well (Figure 12) with both the experimental results and Sobhi and Wu's predictions.

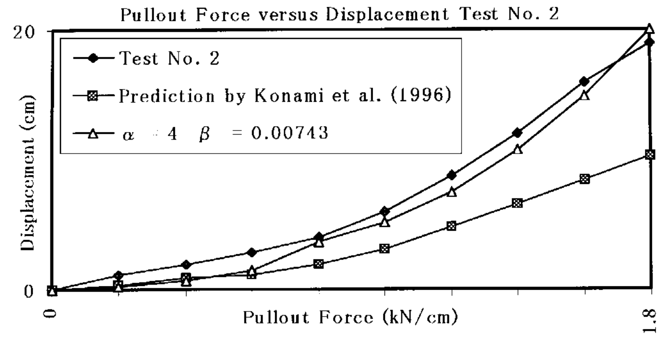

Figure 9. Pullout force vs. displacement response for Test No. 2[7]

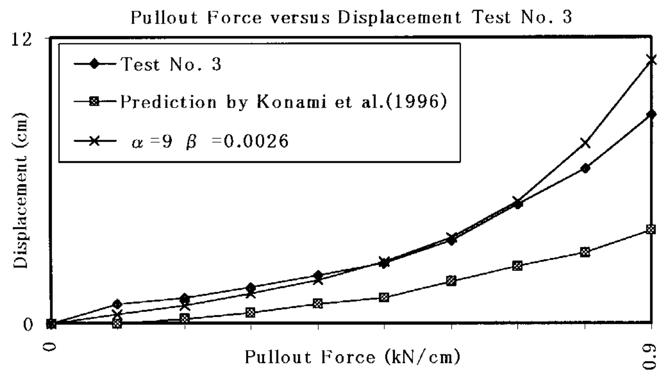

Figure 10. Pullout force vs. displacement response for Test No. 3[7]

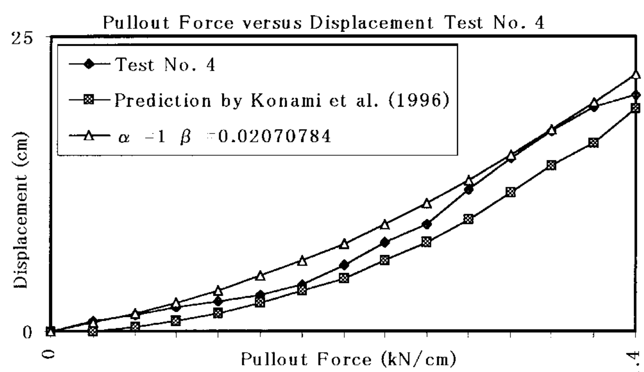

Figure 11. Pullout force vs. displacement response for Test No. 4[7]

Finally, pullout tests on Nylon 6/6 Inclusion ASPR 57 and ASPR 59[21] were analysed. The length, width and thickness of the inclusion were 42, 13.34 cm and 0·598 mm, respectively. The tests were conducted at the confining pressure σ'_n of 24·5 kPa but at displacement rates of 35 and 3·5 μm/s. The interface friction angle of sand was 20–25°. The estimated value of $T_{max} = 2L\sigma'_n$ tan

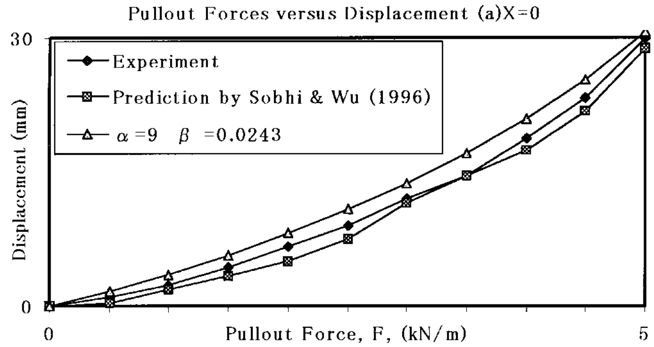

Figure 12. Pullout force vs. displacement response at $X = 0$ end[10]

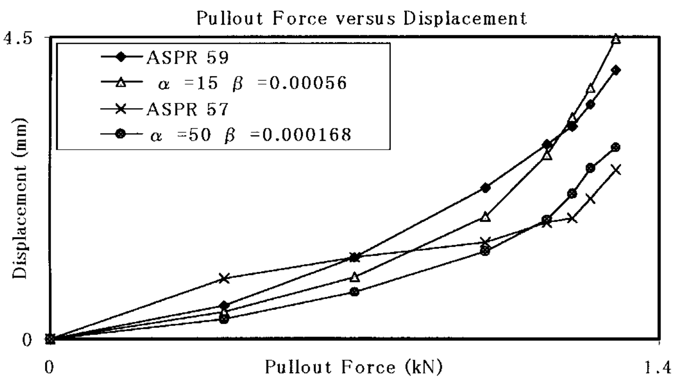

Figure 13. Pullout force vs. displacement response for ASPR 57/59[21]

Table I. Summary of interface pullout test parameters

Tests	σ'_n (kPa)	L (m)	$E_r t_r$ (kN/m)	$\alpha\beta = T_{max}/E_r t_r$	α	β	k_s (kN/m^3)
Konami *et al.*,	86·4	3·5	5970	0·03	6	0·005065	1460
1996	57·6	3·5	5970	0·03	4	0·00743	975
	28·8	3·5	3880	0·023	9	0·0026	1425
	14·4	3·5	3880	0·021	1	0·0207078	160
Sobhi and Wu	40	0·3	31·8	0·218868	9	0·0243	1590
Abramento and	24·5	0·42	975·36	0·0084	15	0·00056	41470
Whittle, 1995	24·5	0·42	975·36	0·0084	50	0·000168	138230

$\phi'_{s/r} = 9{\cdot}596$ kN/m gave the product $\alpha\beta = T_{max}/E_r t_r$, as 0·0084. For tests ASPR 57 and ASPR 59,[21] responses with values of $\alpha = 15$, $\beta = 0{\cdot}00056$ and $\alpha = 50$, $\beta = 0{\cdot}000168$ compare closely with the test results as shown in Figure 13.

The interface interaction parameters for the above pullout experiments are summarized in Table I.

5. CONCLUSIONS

The pullout–displacement response of extensible planar reinforcement is expressed in a differential equation form for a non-linear hyperbolic behaviour of the mobilized unit shear stress with displacement along the length. The governing equation is numerically solved using a finite difference scheme and the Gauss–Siedel iteration method to conduct a parametric study. Two new soil-inclusion interaction terms, the relative stiffness parameter α and the relative displacement parameter β were conceptualized and expressed in non-dimensional form. The first approximation method for the estimation of the interface interaction parameters from pre-failure pullout test results is also proposed.

Normalized pullout force versus displacement responses are presented for various ranges of relative stiffness parameters α and β. Displacement–pullout responses are non-linear particularly for higher values of the relative stiffness parameter α. Comparison of the predicted displacements with those from experiments on pullout tests on polymer strips,[7] geotextile[10] and nylon 6/6 inclusion (ASPR 57/59)[21] show reasonable agreement. Better estimation on soil–reinforcement interaction parameters such as τ, μ, k_s, α and β could improve the accuracy in predictability.

NOTATION

E_r	Young's modulus of reinforcement (kPa)
i	typical node point (non-dimensional)
k_s	initial slope of shear stress-displacement relation (kN/m^3)
L	length of reinforcement (m)
n	number of elements for discretisation (non-dimensional)
q_0	surcharge stress (kPa)
t_r	thickness of reinforcement (m)
T	tensile force at any point, x, along the reinforcement (kN/m)
T_{max}	maximum pullout force in the reinforcement (kN/m)
T^*	$(=T/T_{max})$ (non-dimensional)
$\mathscr{W}$	displacement (m)
w_y	displacement at the yield $(=\tau_m/k_s)$ (m)
W	normalised displacement $(=\mathscr{W}/w_y)$ (non-dimensional)
W_i	normalized displacement of ith element (non-dimensional)
x	co-ordinate along the length of reinforcement (m)
X	normalised co-ordinate $(=x/L)$ (non-dimensional)
Z	depth of the reinforcement (m)

Greek letters

α	normalised interface stiffness $(=2k_sL^2/E_rt_r)$ (non-dimensional)
β	normalised displacement limit $(=\tau_m/k_sL)$ (non-dimensional)
γ'	effective unit weight of the fill (kN/m^3)
ε	axial strain (non-dimensional)
μ	coefficient of friction between soil and reinforcement $(=\tan\phi'_{s/r})$ (non-dimensional)
σ'_n	effective normal stress (kPa)
τ	shear stress along the reinforcement and soil interface (kPa)
τ_m	limiting or maximum interface shear stress (kPa)
$\phi'_{s/r}$	effective interface bond resistance friction angle (degree)

REFERENCES

1. A. McGown, K. Z. Andrawes and M. M. Al-Hasani, 'Effect of inclusion properties on the behaviour of sand', *Geotechnique*, **28**(3), 327–346 (1978).
2. J. K. Mitchell and W. C. B. Villet, 'Reinforcement of slopes and embankments', *National Co-operative Highway Research Program report No. 290*, Transportation Research Board, National Research Council, Washington, D.C. U.S.A. 1987, 323.
3. B. R. Cristopher, S. A. Gill, J. P. Giroud, I. Juran, J. K. Mitchell, F. Schlosser and J. Dunnicliff, 'Reinforced soil structures', Vol I, *Design and Construction Guidelines*, Federal Highway Administration Report No. FHWA-RD-89-043, Washington, D. C., U.S.A. 1990.
4. R. A. Jewell and C. P. Wroth, 'Direct shear tests on reinforced sand', *Geotechnique*, **37**(1), 53–68 (1987)
5. F. Schlosser and P. de Buhan, 'Theory and design related to the performance of reinforced soil walls', *Proc. Int. Reinforced Soil Conf.*, Glasgow, 1990, pp. 1–14.
6. R. A. Jewell, 'Links between the testing, modelling and design of reinforced soil', Keynote Lecture, Proc. *Int. Symp on Earth Reinforcement Practice*. Fukuoka, Japan, Vol. 2, Bond Capacity, *Geotechnique*, **40**(3), 513–518 (1992).
7. T. Konami, S. Imaizumi and S. Takahashi, 'Elastic considerations of field pull-out tests on polymer strip', *Proc. Int. Symp. on Earth Reinforcement*, Kyushu, Japan, 1996, pp. 57–62.
8. M. Abramento and J. A. Whittle, 'Analysis of pullout tests for planar reinforcements in soil', *J. Geotech. Engng. ASCE*. **121**(6), 476–485 (1995).
9. P. Segrestin and M. Bastick, 'Comparative study and measurement of the pullout capacity of extensible and inextensible reinforcements', *Proc. Int. Symp. on Earth Reinforcement*, Kyushu Japan, 1996, pp. 139–144.
10. S. Sobhi and J. T. H. Wu, 'Interface pullout formula for extensible sheet reinforcement', Geosynthetics Int., **3**(5), 1996, pp. 565–581.
11. P. V. Long, D. T. Bergado and A. S. Balasubramaniam, 'Interaction between soil and geotextile reinforcement', *Ground Improvement, Reinforcement, and Treatment Developments 1987 to 1997*, ASCE Special Publications No. 69, 1997, pp. 560–578.
12. I. Yogarajah and K. C. Yeo, 'Finite element modelling of pull-out tests with load and strain measurements', Geotextiles Geomembranes, Vol. 13, pp. 43–54 (1994).
13. A. M. Britto and M. J. Gunn, '*Critical State Soil Mechanics via Finite Elements*', Ellis Horwood, Chichester, U.K. 1990.
14. R. E. Goodman, R. L. Taylor and T. L. Brekke, 'A model for the mechanics of jointed rocks', *J. Soil Mech. Engng Foundations Div., ASCE*, **94,** 637–659 (1968).
15. V. N. Kaliakin and J. Lin, 'Insight into deficiencies associated with commonly used zero-thickness interface elements', *Comput. Geotech.*, **17,** 225–252 (1995).
16. C. S. Desai, M. M. Zaman, J. G. Lightner and H. J. Siriwardene. 'Thin layer element for interfaces and joints', *Int. J. Numer. Anal. Meth. Geomech.*, **8,** 19–43 (1984).
17. D. T. Bergado, J. C. Chai and N. Miura, 'FE analysis of grid reinforced embankment system on soft Bangkok clay', Comput Geotech, **17,** 447–471 (1995).
18. M. R. Madhav, N. Gurung and Y. Iwao, 'A theoretical model for pull-out response of extensible reinforcements', *Geosynthetics Int.*, **5**(4), 399–424 (1998).
19. Z. Cai and R. J. Bathurst, 'Seismic response analysis of geosynthetic reinforced soil segmental retaining walls by finite element method', Comput. Geotech., **17,** 523–546 (1995).
20. G. W. Clough and J. M. Duncan, 'Finite element analysis of retaining wall behaviour', *J. Soil Mech. Foundation Engng, ASCE*, **97**(SM12), 1657–1673 (1971).
21. M. Abramento and J. A. Whittle, 'Experimental evaluation of pullout analyses for planar reinforcements', *J. Geotech., Engng, ASCE*, **121**(6), 486–492 (1995).

